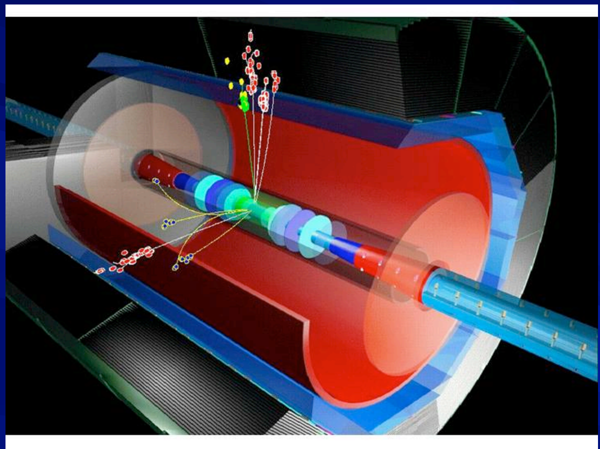
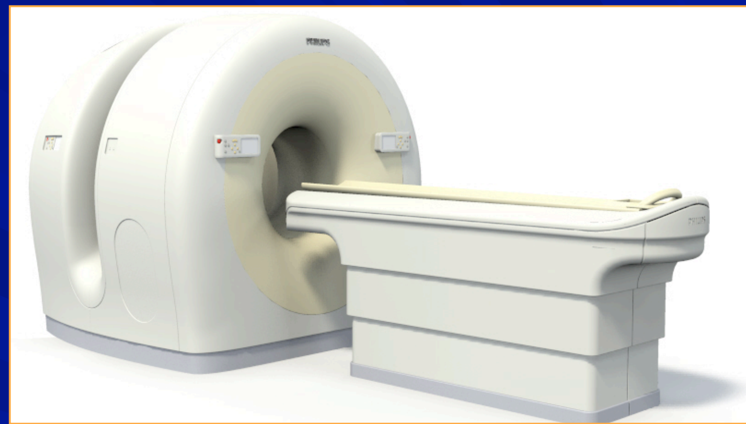
Detectors in particle physics and medical applications

An introduction to basic radiation detectors (from physics to medical)





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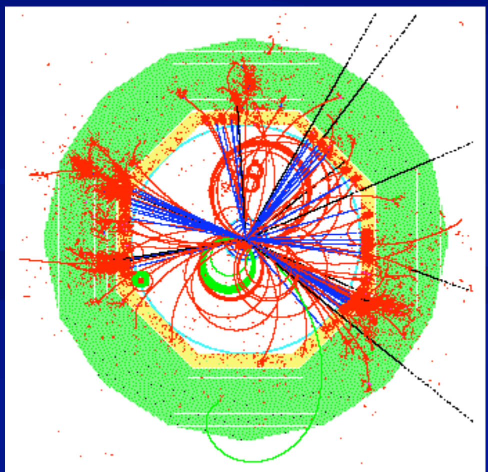
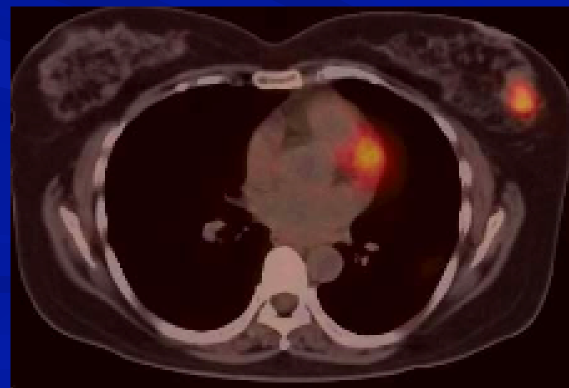
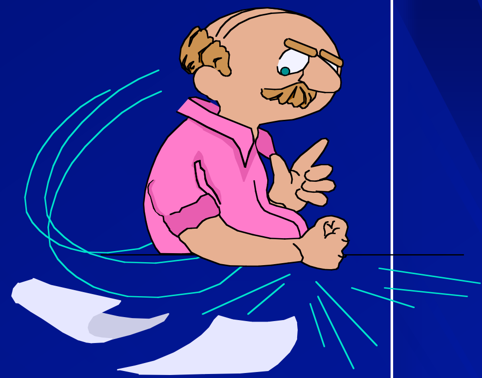


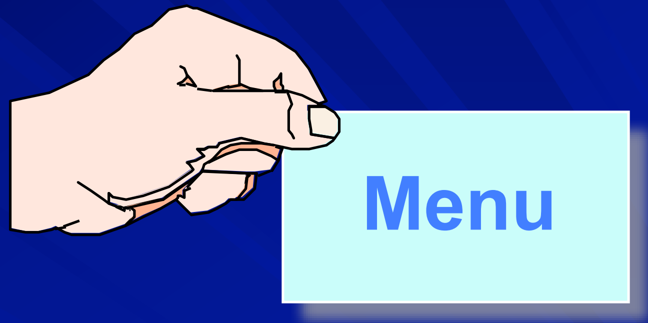


Goals of these presentations

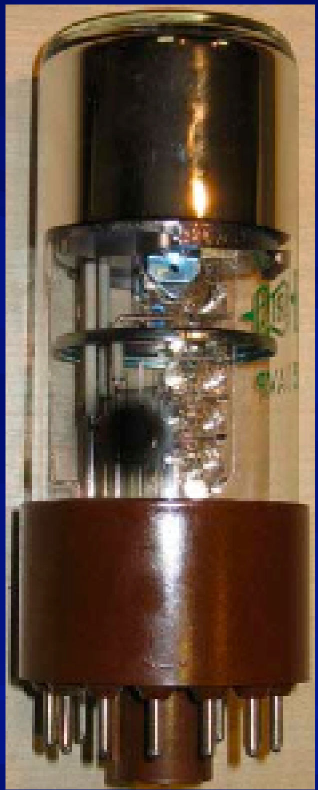


- Don't be scarred ! !
- Simple & illustrated global overview of the basic radiation detector technologies & principles
- A little bit of history ....
- Evolution from the origin to the state of the art
- What we can expect in the near future
- Illustration in Physics <u>and</u> Medical

- The basic principles of Radiation detectors
  - Photodetectors
  - Gazeous detectors
  - Solid state detectors
- Signals & data treatment
  - Electronics
  - Trigger
  - Data Acquisition & Analysis
- Two medical applications
  - (from diagnostic to therapy)
    - Positron Emission Tomography (PET)
    - Hadrontherapy



Photodetectors



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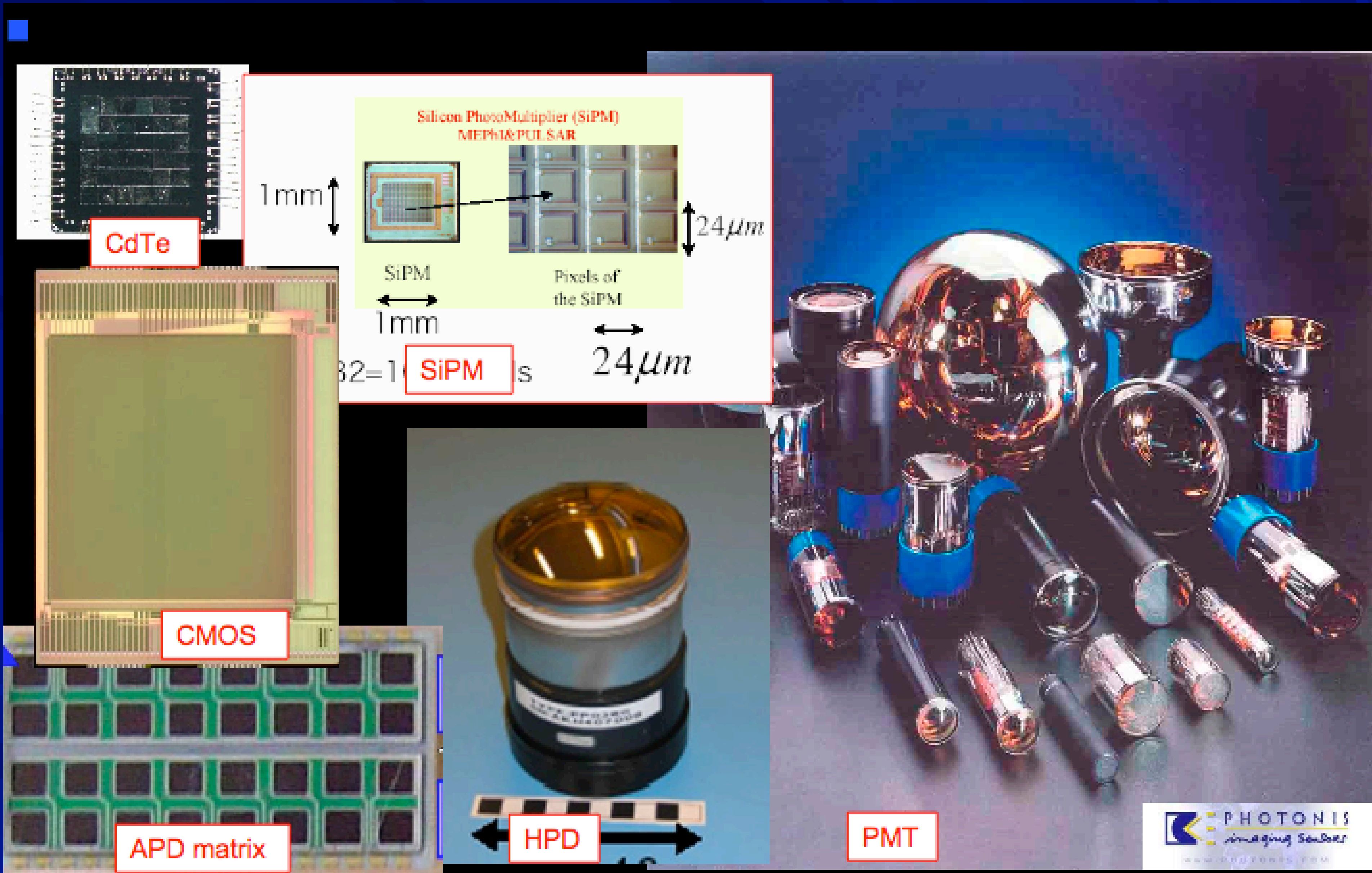
A large variety, but a similar modelization



Sources

- Most important sources were borrowed from the web pages of
  - Hamamatsu: http://sales.hamamatsu.com/en/home.php
  - Photonis: http://www.photonis.com/
  - Electron Tubes Limited :http://www.electrontubes.com/
  - e2v Technologies :http://e2vtechnologies.com/(formerly EEV)
  - Delft Electronics Products:http://www.dep.nl/
  - SensL:http://www.sensl.com/
  - Micron :http://www.micron.com/
  - and many others

- from the web pages of Amos Breskin
  http://www.weizmann.ac.il/home/detlab/

And from many other lectures and presentations, in particular by:
Philippe Mangeot(CEA/DAPNIA)
Katsushi Arisaka (UCLA)
Thomas Patzak (IN2P3 / APC)
Jerry Blazey(Northern Illinois University)

Thank you and many apologizes (overall for the ones I forgot to cite!)

Applications of photodetectors --> Everywhere !

Look around you, they are everywhere, you don 't even know or notice !

- Media *(digital camera, camcorder, cell phones, CD reader…)*
- Telecom *(optical fiber links, optical couplers…)*
- Laser applications *(measurement, gas analysis, barcode readers…)*
- Medicine *(gamma and PET camera, digital X rays, endoscopies…)*
- Biology *(DNA sequencing, Immuno-assay, biochip…*
- Industry *(chemical and surface analysis, process control, shape analysis…)*
- Defense *(night vision, earth observation…)*
- Mining *(oil well logging, rock analysis…)*
- Physics *(a rather small part of the market !)*
  - Solid state, synchrotron radiation, plasma science
  - Particle and nuclear physics
  - Astronomy and astrophysics

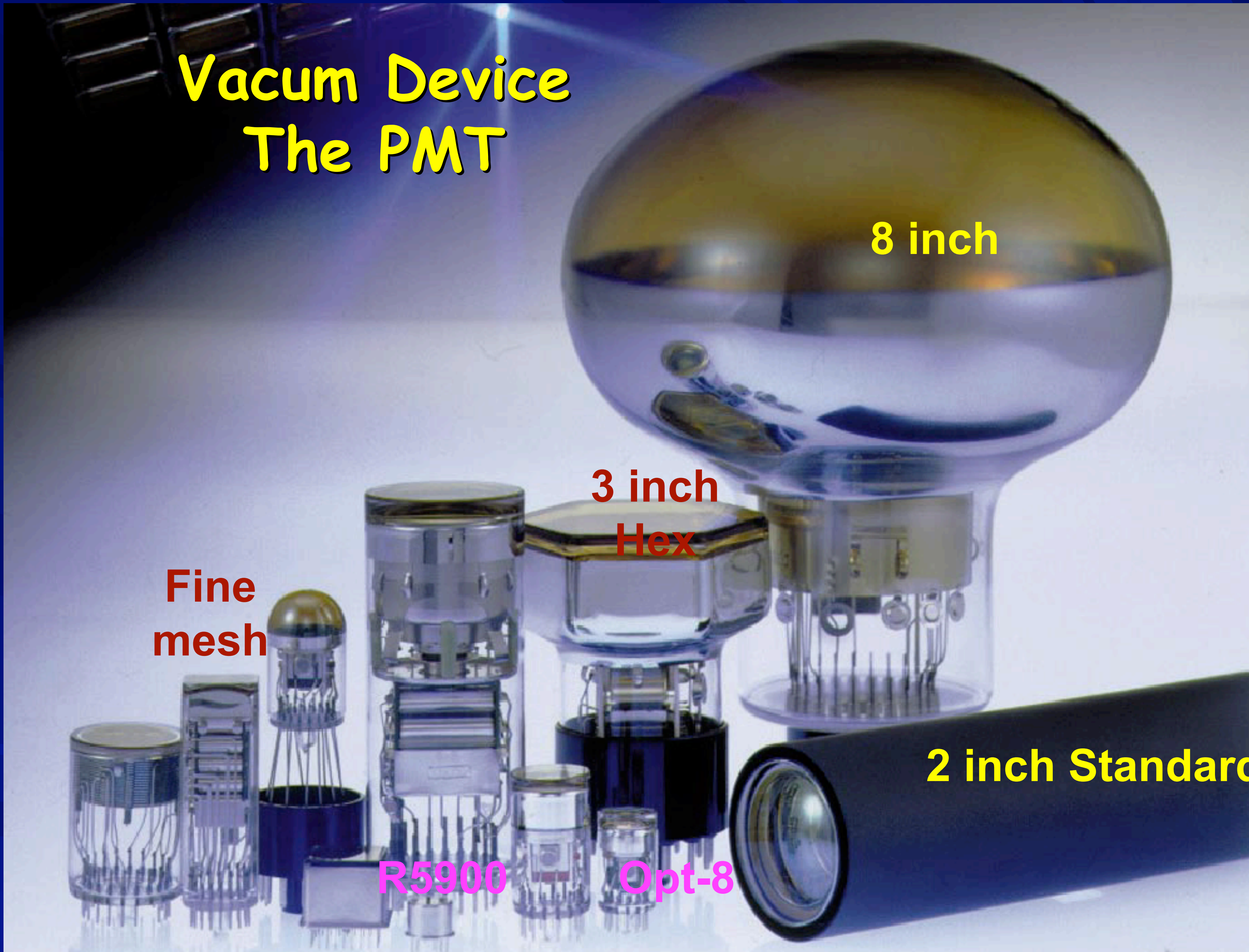
Types of photodetectors

- Vacuum devices
  - Photomultiplier
  - Multichannel Plates
  - Hybrid photon detectors
- Solid state devices
  - Photodiodes, phototransistors and PIN diodes
  - Avalanche photodiodes (APD)
  - Silicon photo multipliers (SiPM)
  - Imaging arrays photo sensor
    - Charge coupled devices
    - CMOS Active Pixel Sensor
    - a:SiHThin Film Transistor array
- Gaseous photodetectors
  - Drift and MWPC
    - Gas photocathode
    - Solid photocathode
  - Micropatterngas chamber

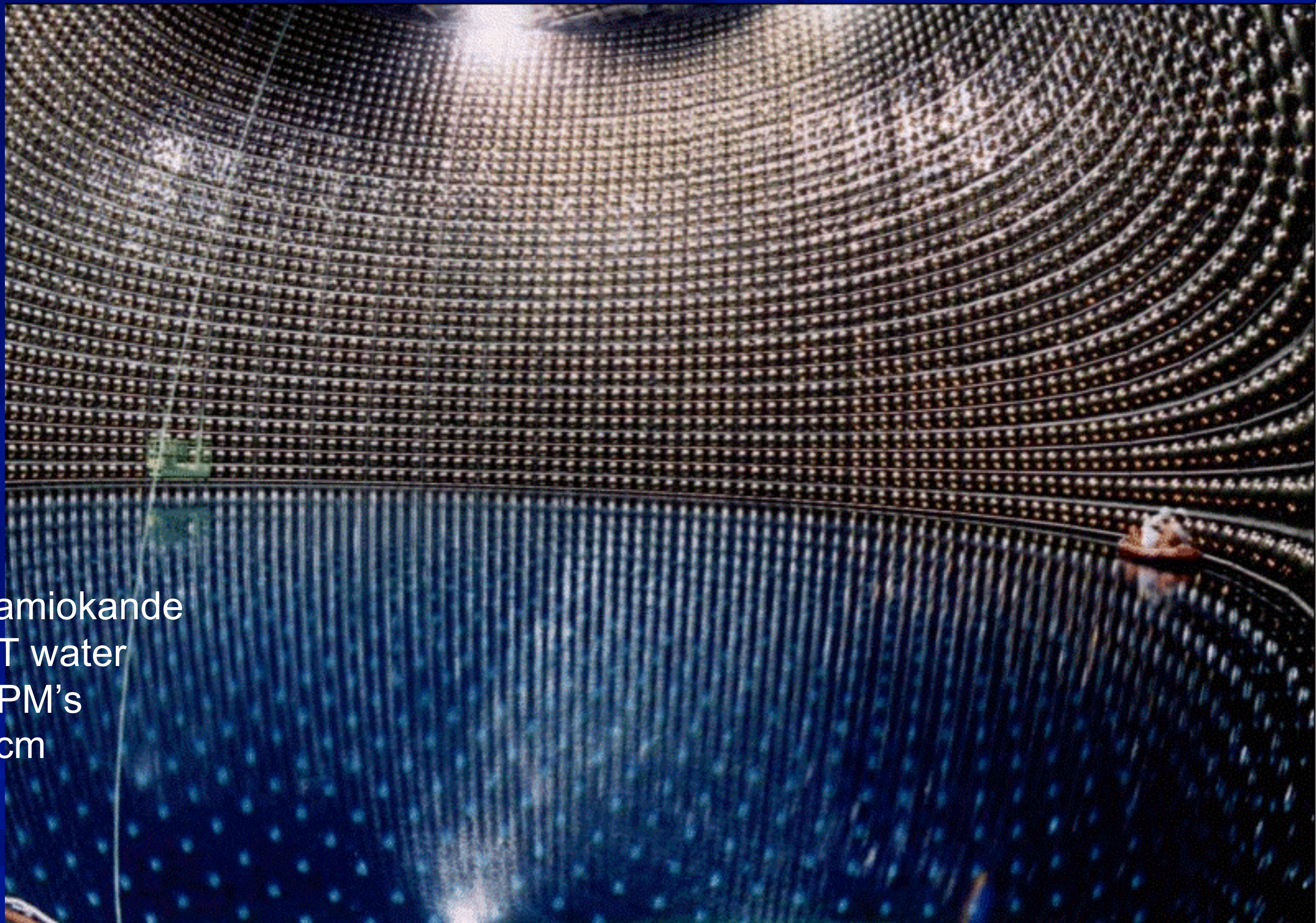
PMT

- More than 90 years of optimisation: The first photomultiplier was built 1913 by Elster and Geiter 8 years after Einstein proposed the concept of the work function.
- PMTs are a commercial product since 70 years.
- Even so the progress during the last years is remarkable: the bulky shape turned into a flat design with very good effective area.
- They come in many different shapes, size (up to 20"!) and performances.
- One of the most important market is medical imaging 300000 PMT'syear.
  - 2000 gammas camera/year, x 80 PMT's
  - 200 PET cameras (800 PMT's each)

Vacum Device
The PMT

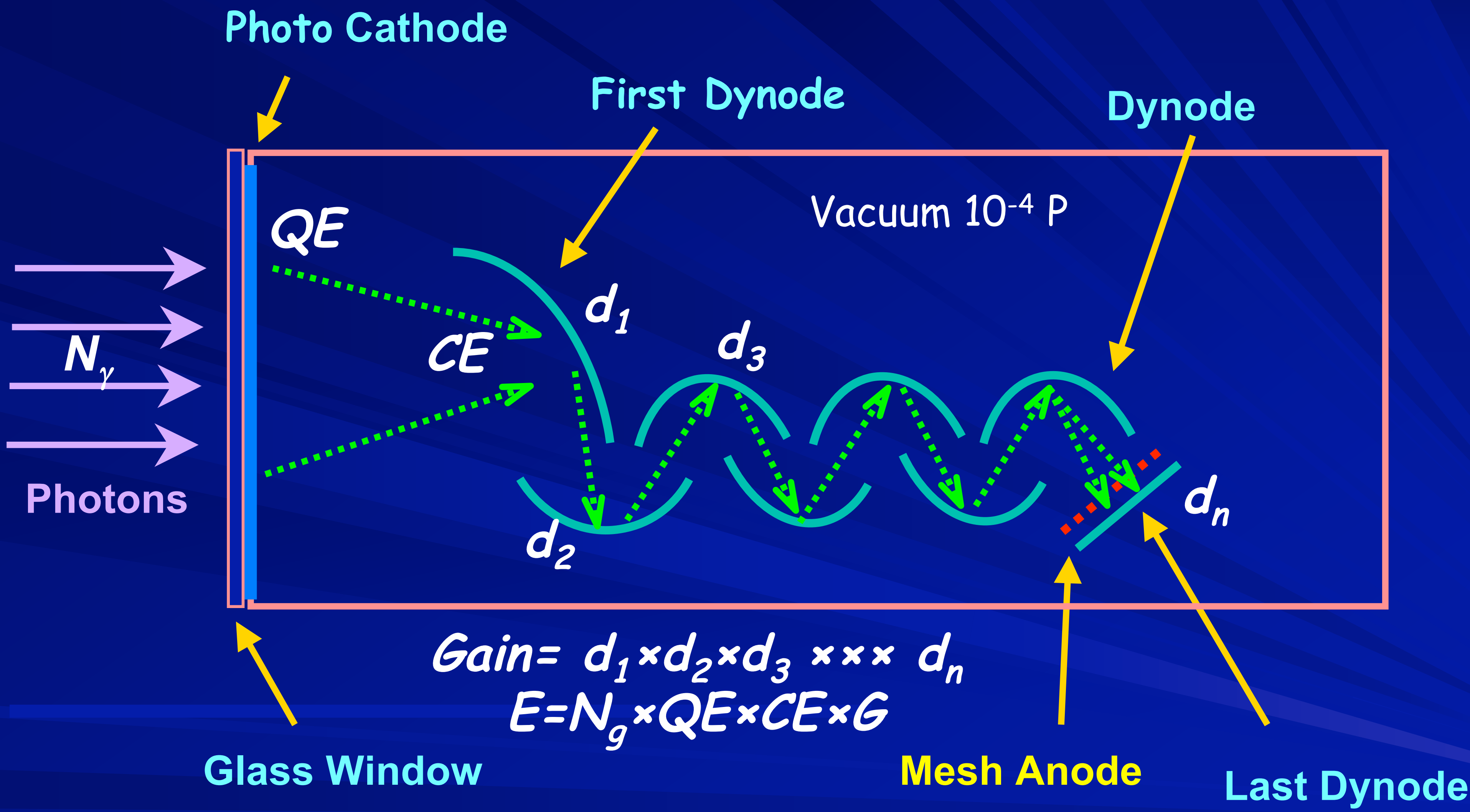


Super-Kamiokande



Super Kamiokande
- 50000 T water
- 11200 PM's
- Φ = 50cm

Structure of Linear-focus PMT



QE = Quantum Efficiency
CC = Collection Efficiency

The first dynode secondary emission coefficient dominates

Quantum Efficiency (QE)

- Definition

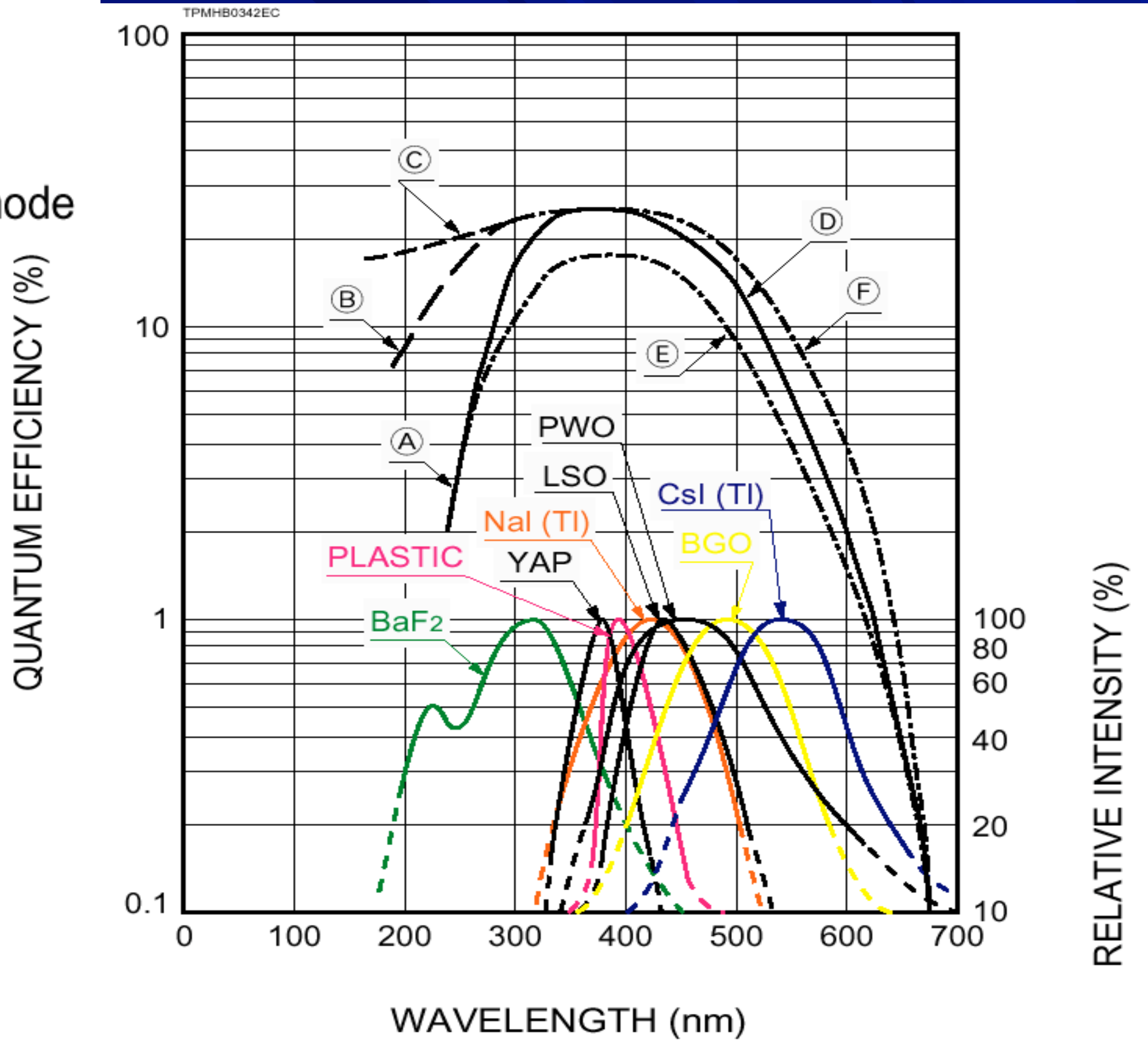
$$QE \equiv \frac{(\#\,Emitted\_Photoelectrons)}{(\#\,Insident\_Photons)} = \frac{N_{pe}}{N_{\gamma}}$$

Photocathode Quantum Efficiency (QE)

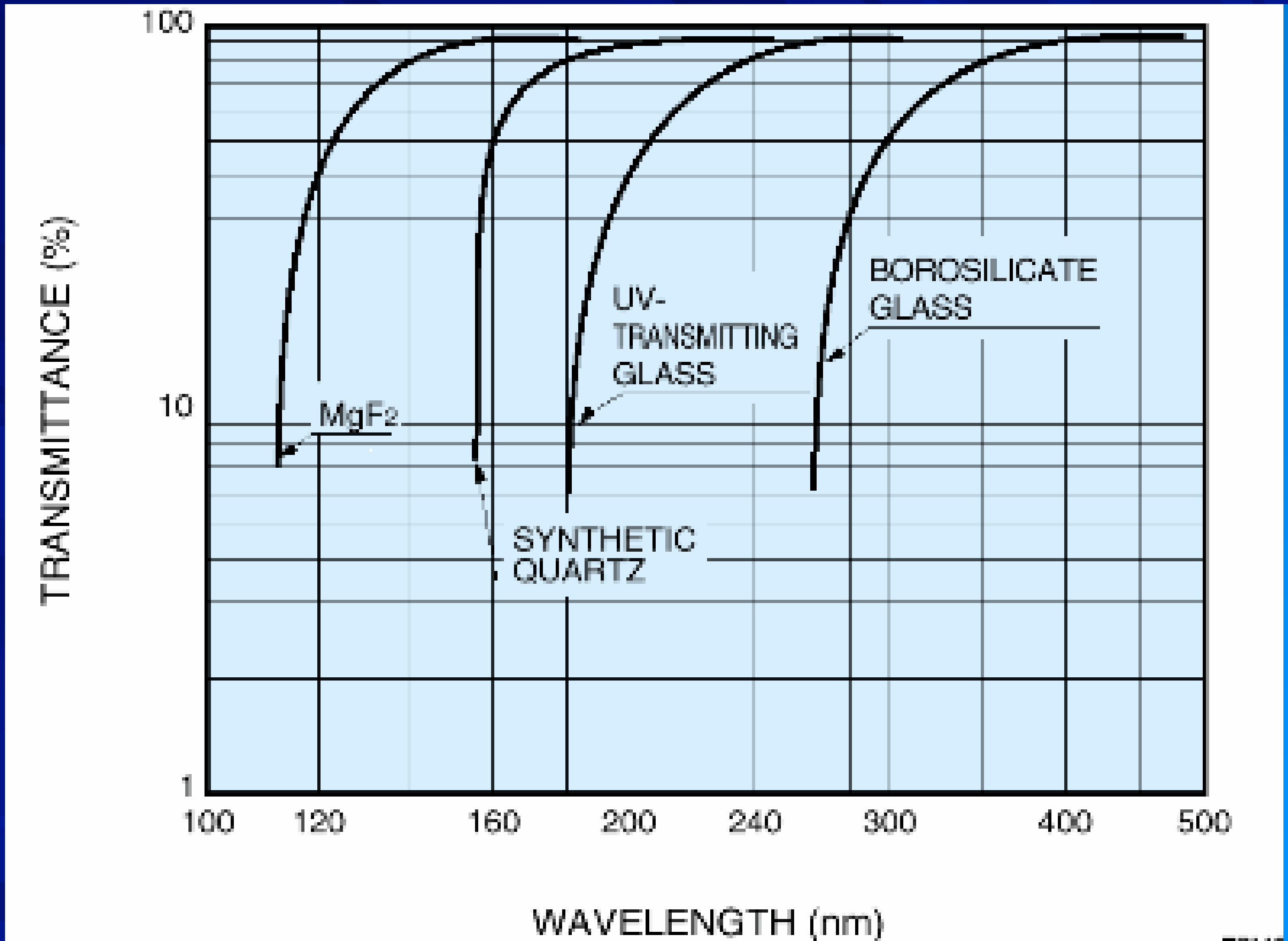
Ⓐ: Borosilicate Glass
Ⓑ: UV Glass
Ⓒ: Synthetic Silica
Ⓓ: Bialkali Photocathode
Ⓔ: High Temp. Bialkali Photocathode
Ⓕ: Extended Green Bialkali Photocathode

Bialkali:
Sb-Rb-Cs
Sb-K-Cs

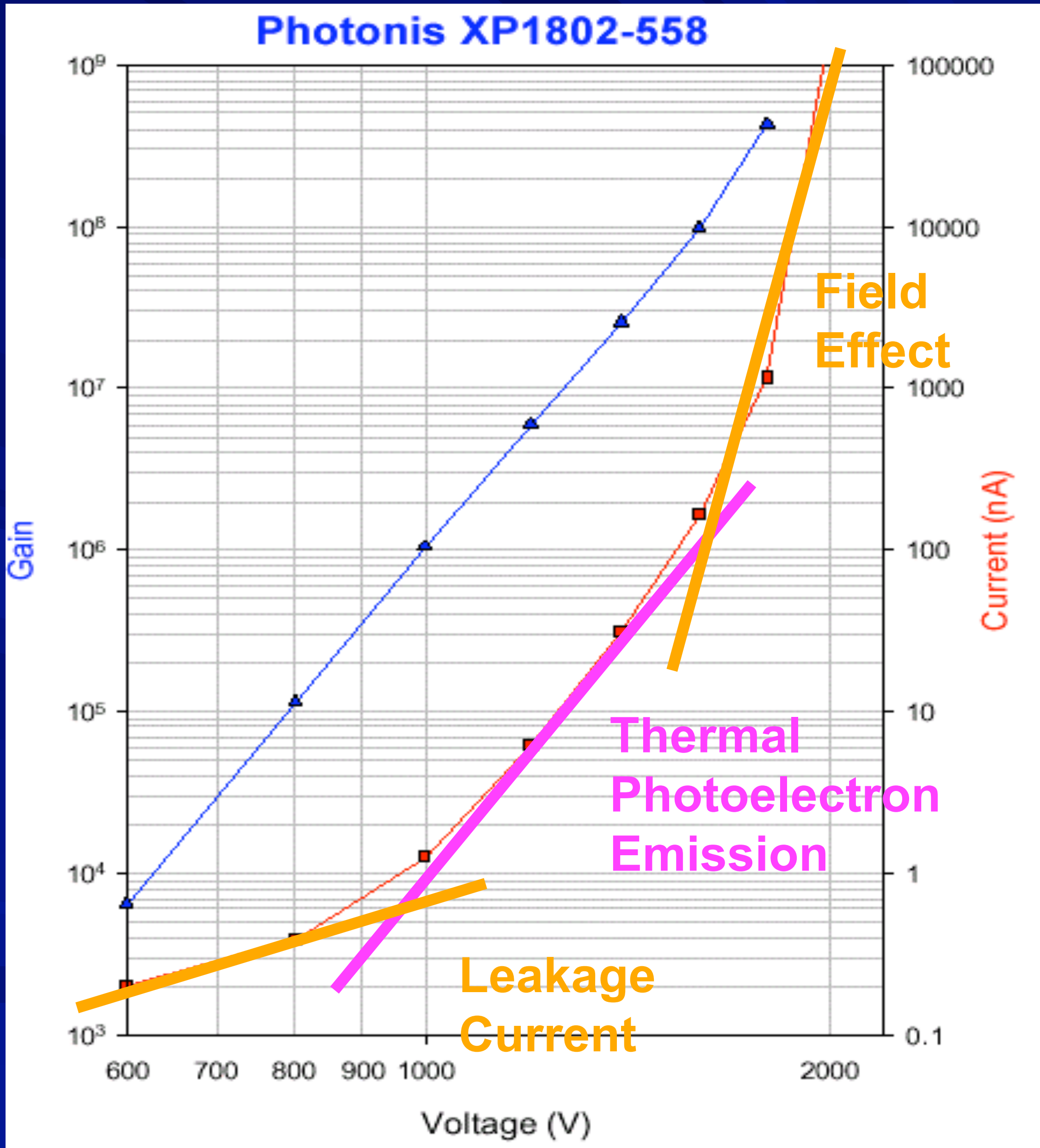
Comparison to emission spectra of common scintillator scintillator materials



Transmittance of glass windows

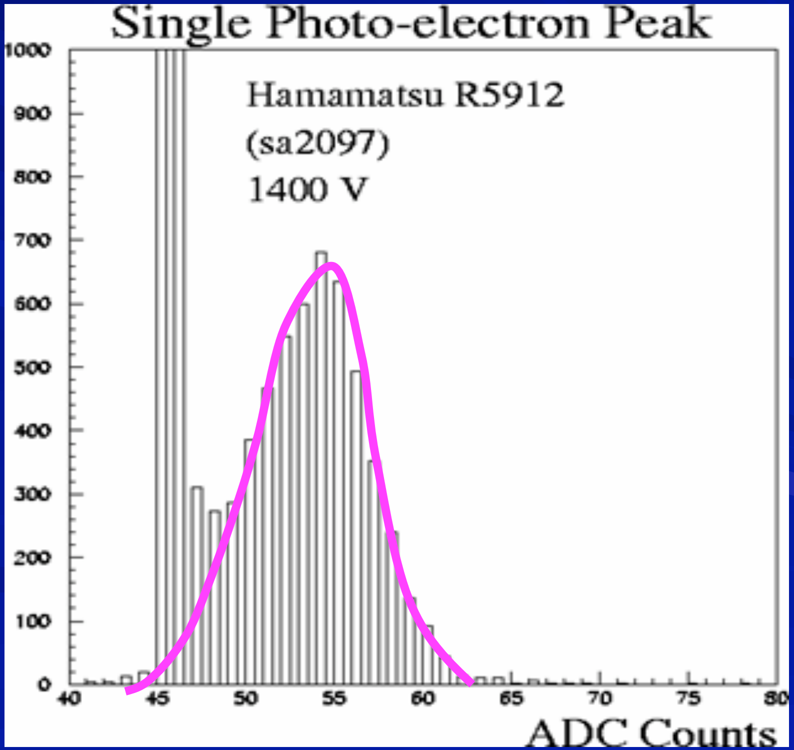


Gain and Dark Current vs. HV



PMT Main parameters and performances

- Quantum Efficiency (QE) 20 to 30% @ 400 nm
- Photoelectron Collection Efficiency (CE) 70 to 90%
- Gain (G) up to 10^7
- Excess Noise Factor (ENF) ~ 1.3
- Energy Resolution (σ/E)



Photomultiplier: Summary

Advantages

A very big sensitive area is possible. Photomultipliers with 50 cm diameter are available.

High gain up to 10^7. The output signal can directly be processed with standard electronics.

Single photon response.

Insensitive to environment effects like temperature.

Excellent timing. The risetime of the output signal can be well below 1 ns. There exist special PMTs with very small Transit Time Spread (< 250 ps).

Prices go down: more automated production, less parts.

Less than 20 $/readout channel.

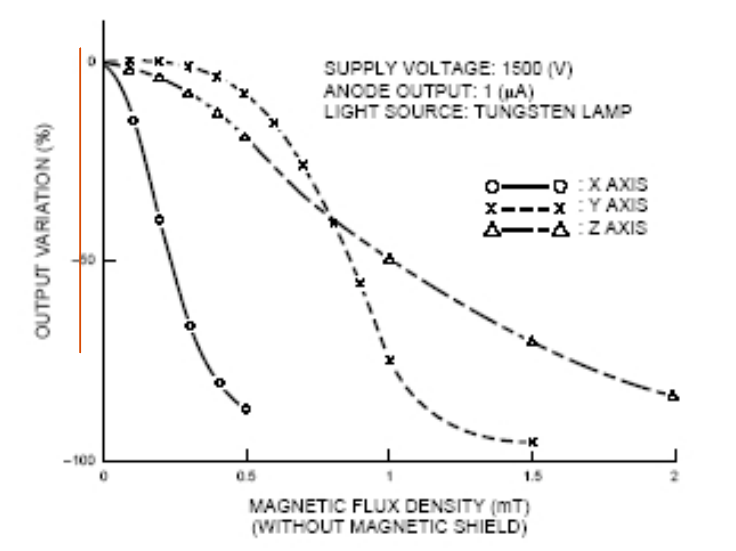
Disadvantages:

PMTs are very sensitive to magnetic fields

Low quantum efficiency of 25%.

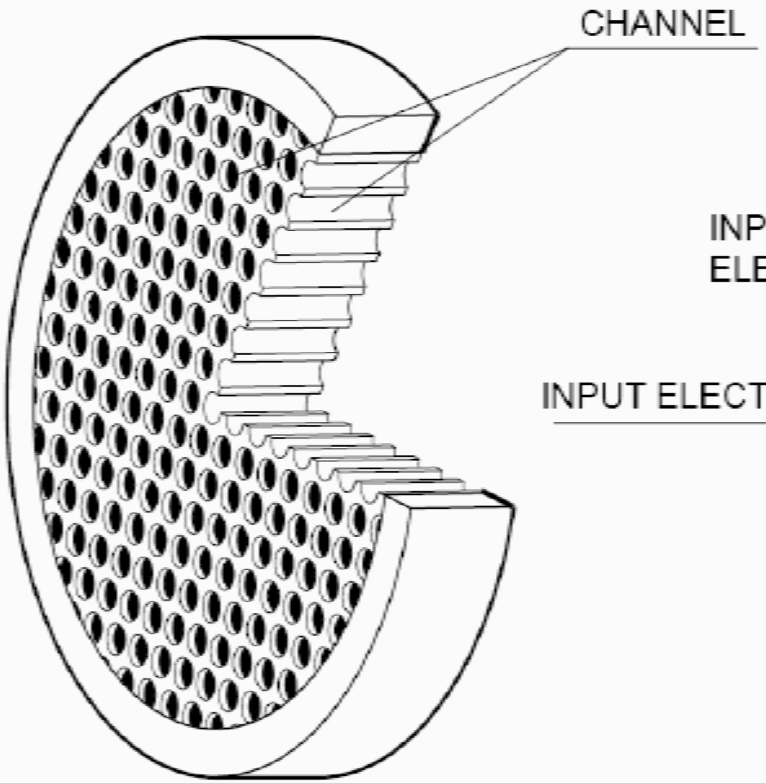
High QE photocathodes are available (GaAsP, 45%) but expensive.

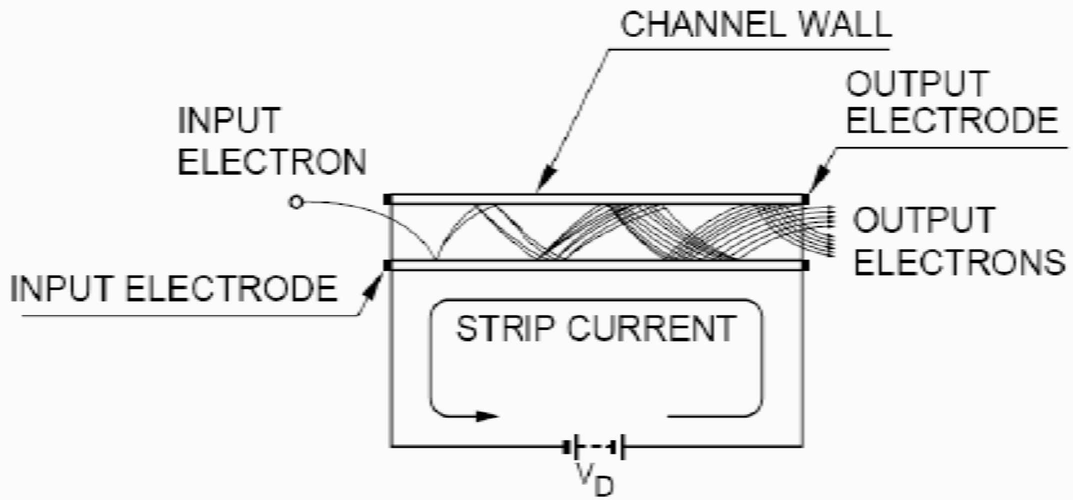
High voltage and high power required. Need high current in a voltage divider.



Multi Channel Plate : MCP

- Structure and principle





(a) Schematic structure of an MCP

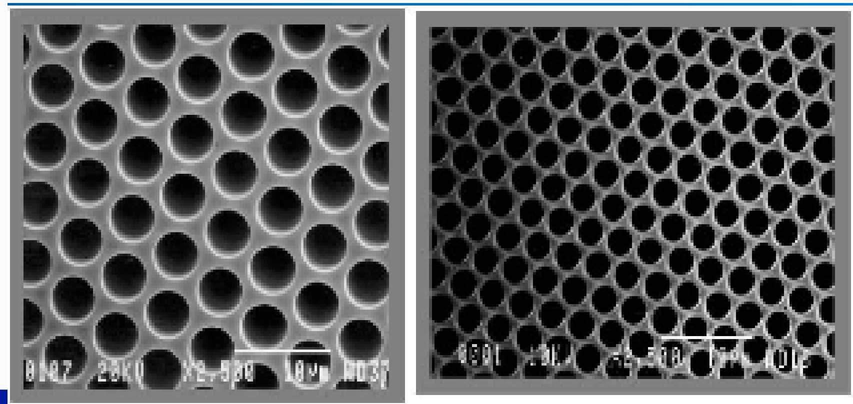
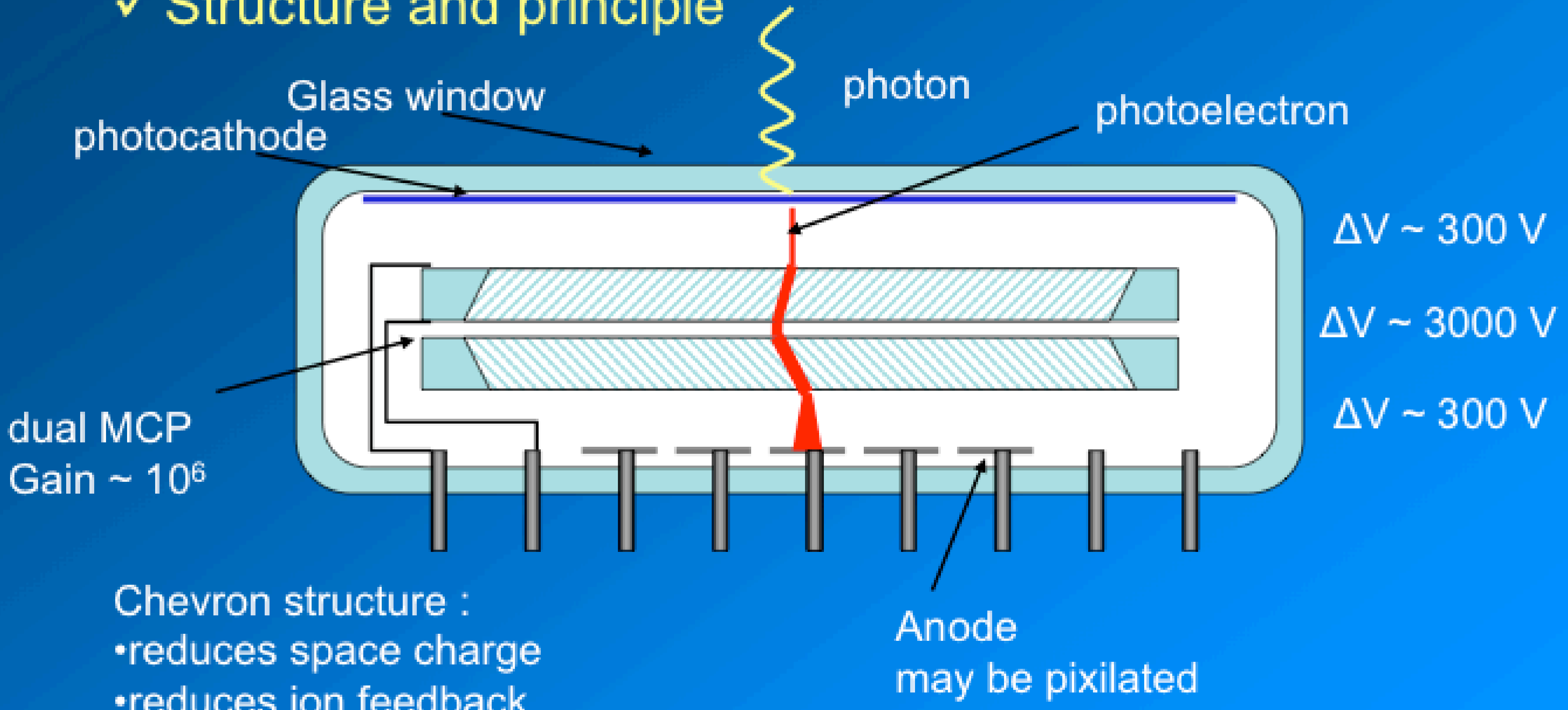


Figure 2 – Comparison of 6micron pore and 2 micron pore MCP's (same magnification)

MCP-PMT Operation

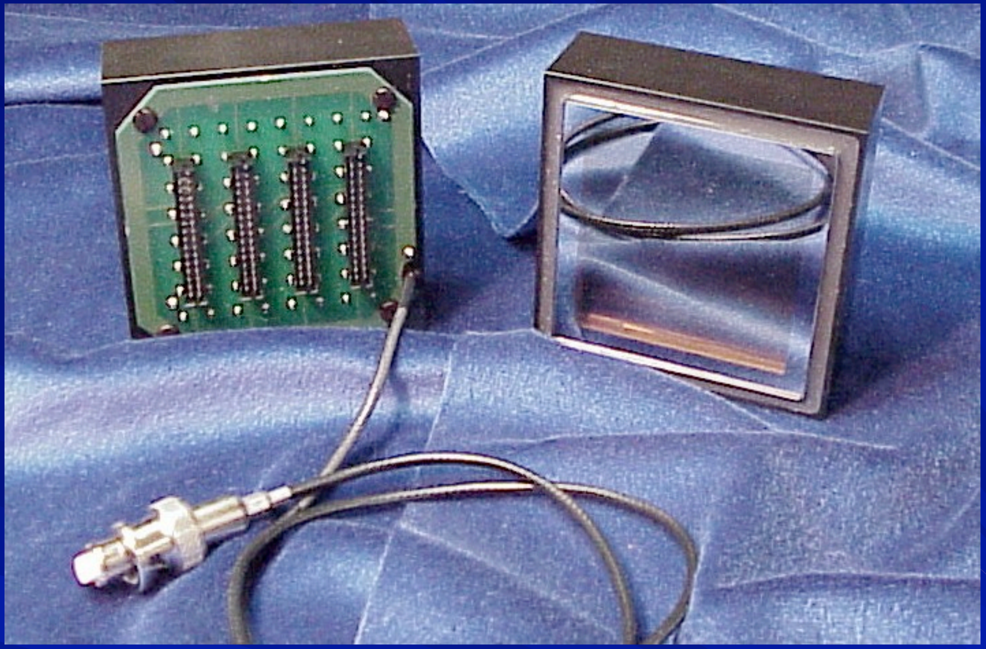
✓ Structure and principle



Chevron structure :
- reduces space charge
- reduces ion feedback
- Increases gain

MCP (2)

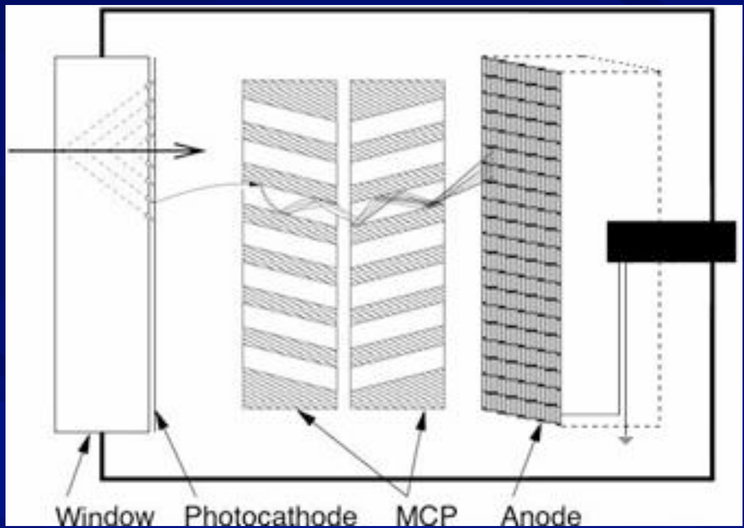
- Two inch *square flat* PMT with dual MCP multiplier.
- Anodes, 2x2, 8x8 and 32 x 32 configurations.
- Improved Open Area Ratio device now available
- Bi-alkali cathode on quartz faceplate.
- *Easily tiled, low profile, excellent time resolution, excellent uniformity.*

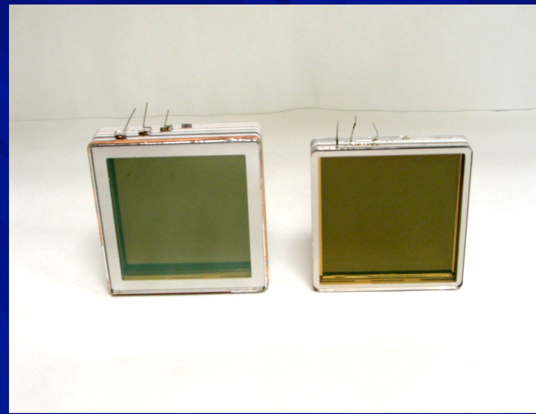


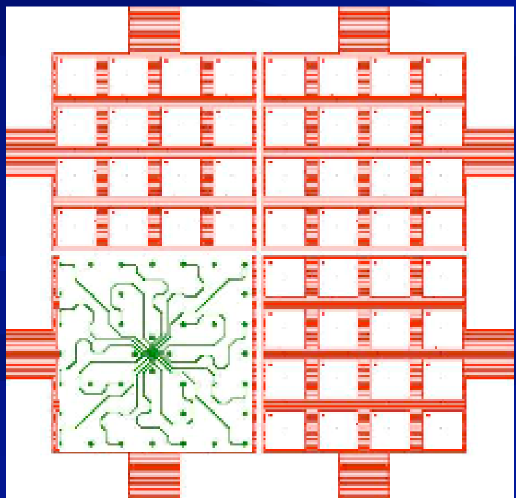
Photonis-Burle

- Applications
  - Light or image intensifier, night and IR vision

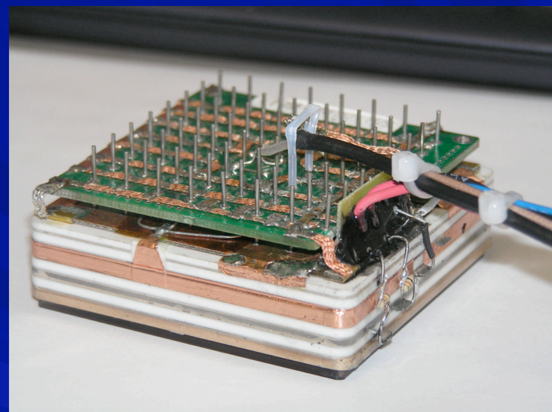
New development
(UC Chicago,ANL,SLAC,LBL, Saclay,Photonis)





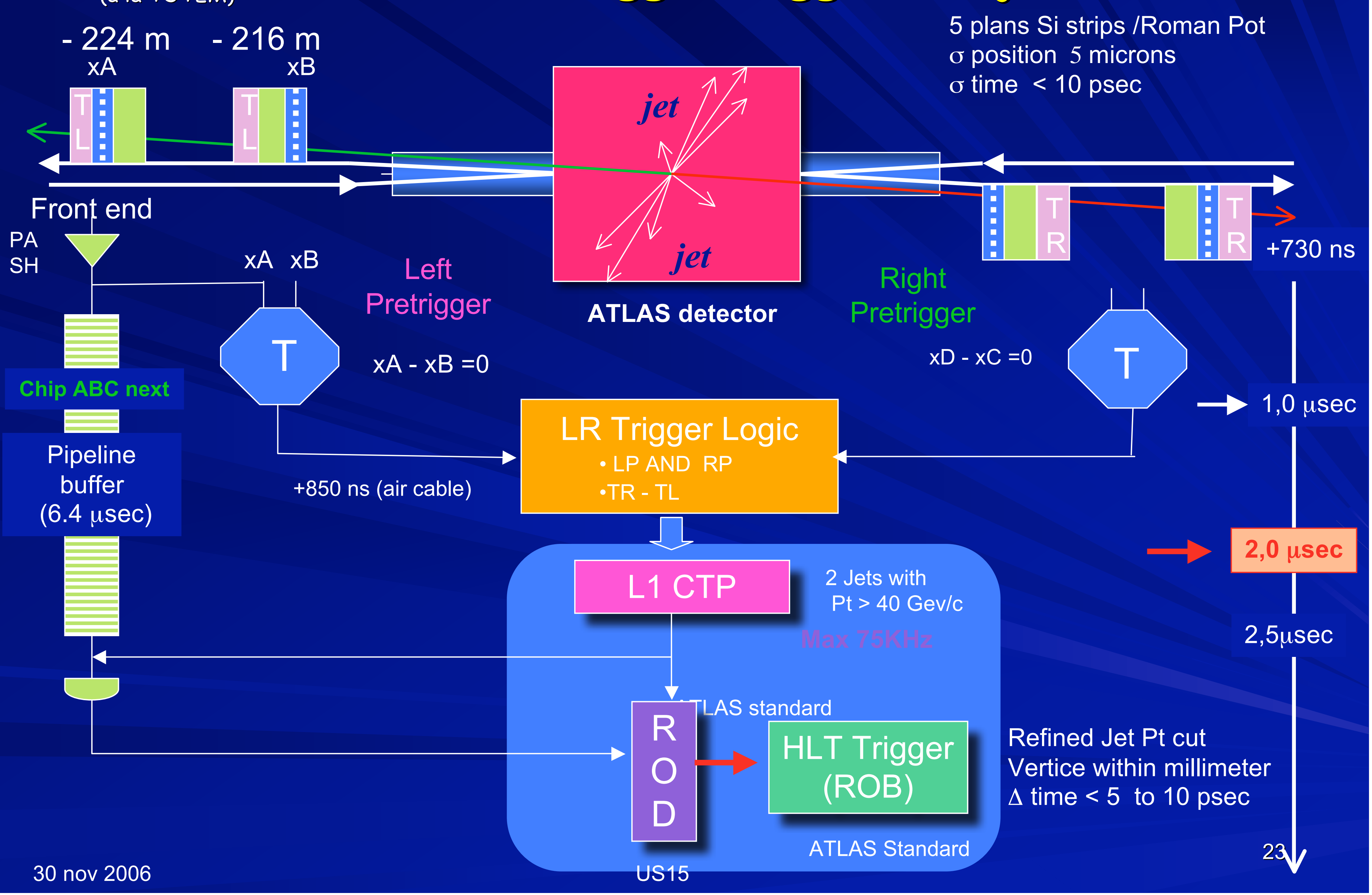


Plus new electronics Architecture



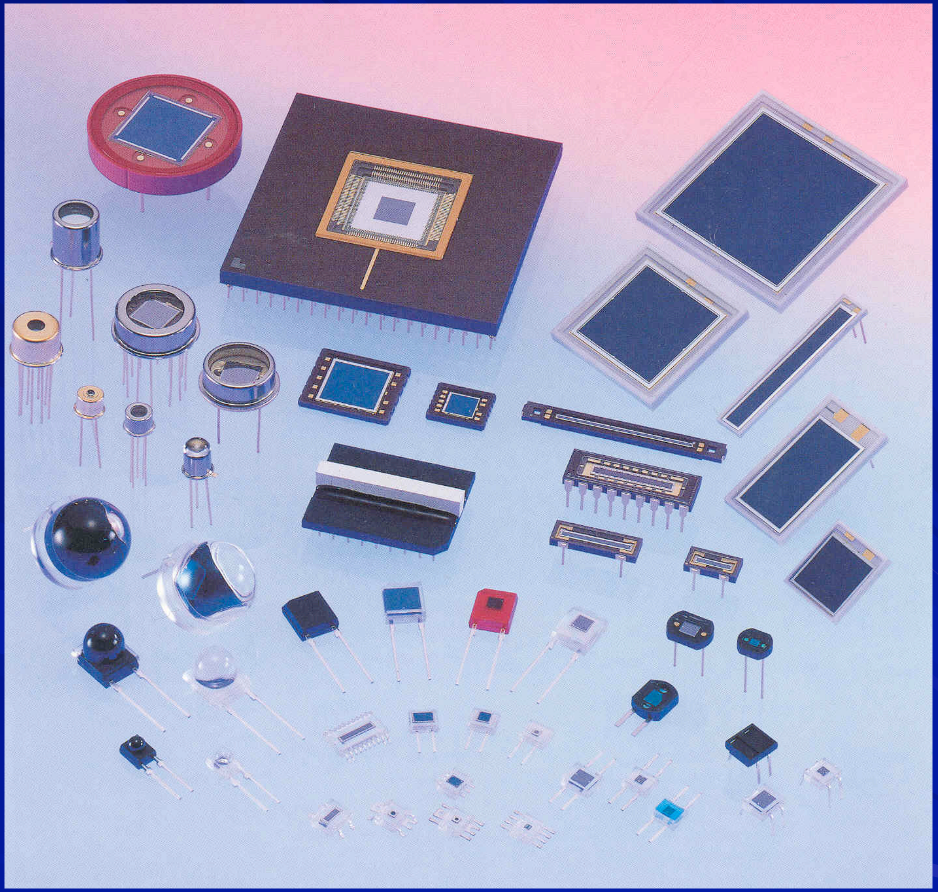
- Application
  - Physics Ultra fast timing TOF (few psec)
  - Medical (30 psec TOF for PET)

Diffractive Higgs Trigger Project

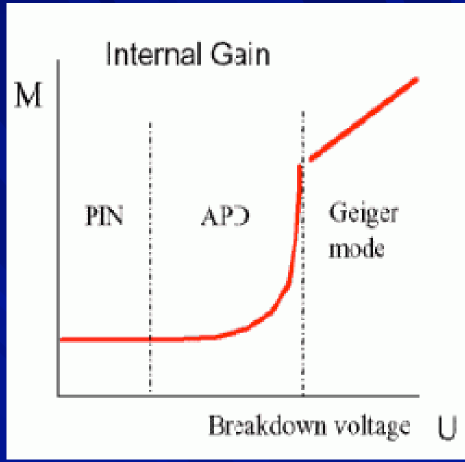


Semiconductor devices: PIN Diodes

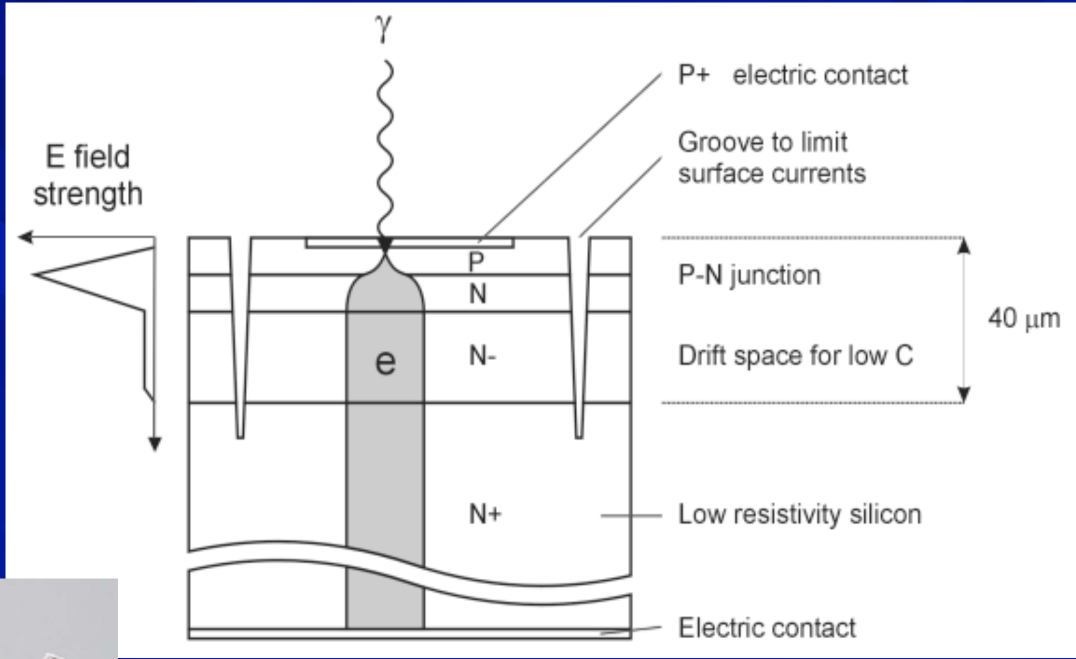
- The PIN diode is a very successful device. It is used in all big calorimeters in high energy physics (Cleo, L3, Crystal Barrel, Barbar, Belle ....)
- Limited use in physical medicine because PIN diodes have no internal gain. They need a low noise amplifier which adds to the costs, makes the output signal (rise and fall time) slow and reduces the energy resolution at low energies.
- Otherwise the PIN diode is the simplest, most reliable and cheapest photosensor.



Semiconductor devices: Avalanche Photodiodes (APD)

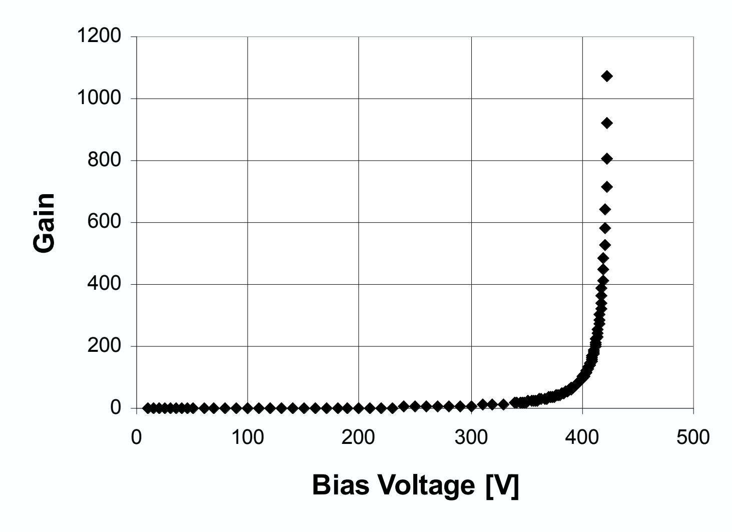


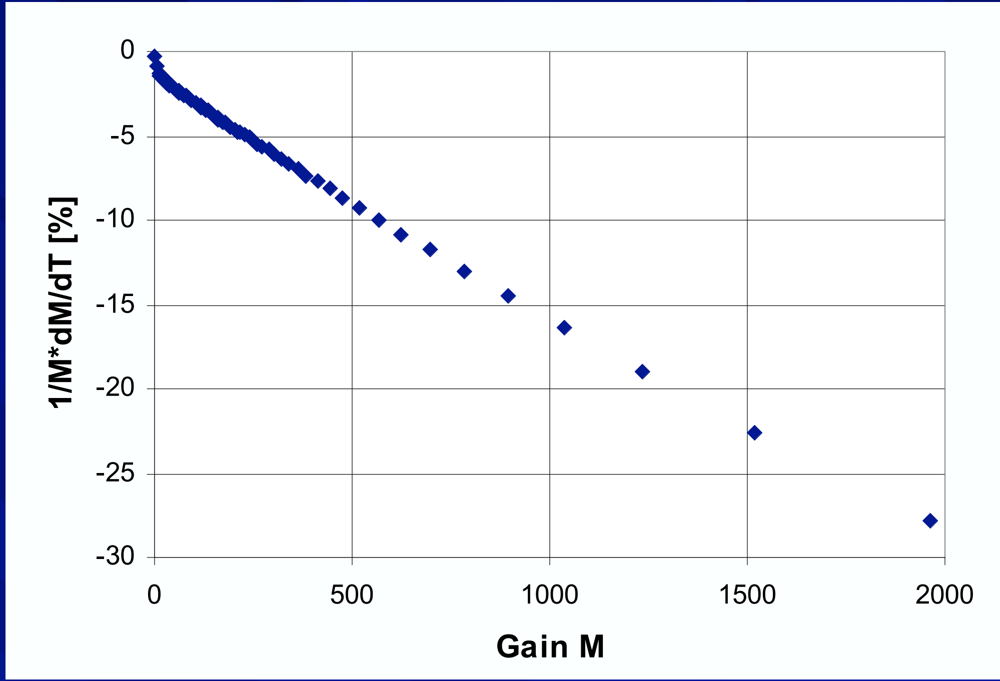
- An Avalanche PhotoDiode (APD) combines the advantages of a PIN photodiode (cheap, small, high QE, insensitivity to magnet fields ...) and those of a photomultiplier (gain and speed).
  - Photons create electron-hole pairs in the thin p-layer on top of the APD. The electrons drift to the high field region at the p-n junction where they create secondary electrons by ionization which then create tertiary and so on. An avalanche is formed.



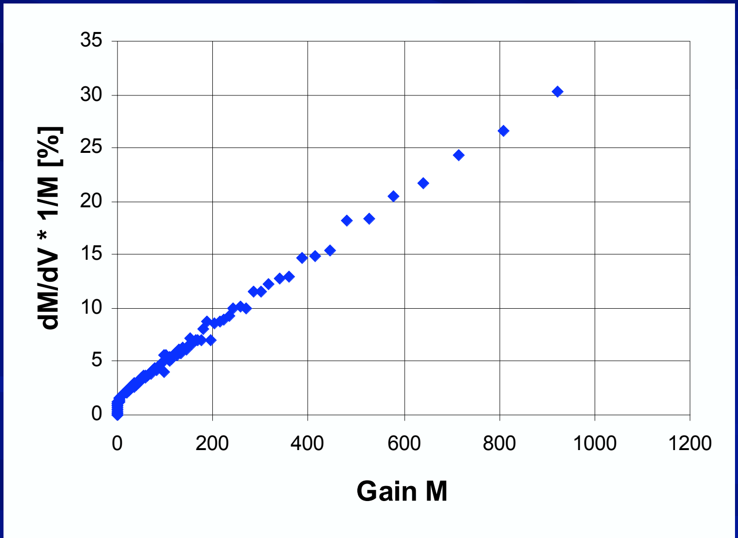
  - The gain of APDs can be 1000 and more.

Avalanche Photodiodes: Stability



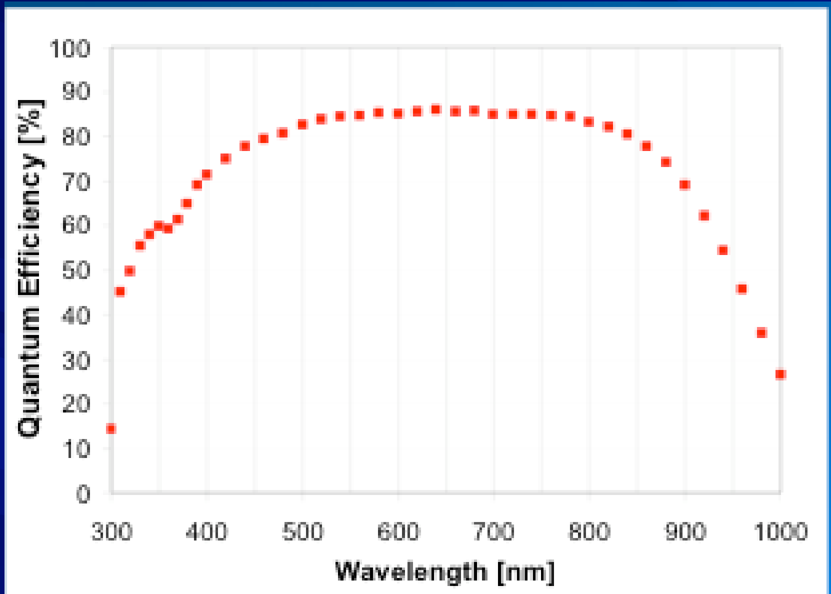


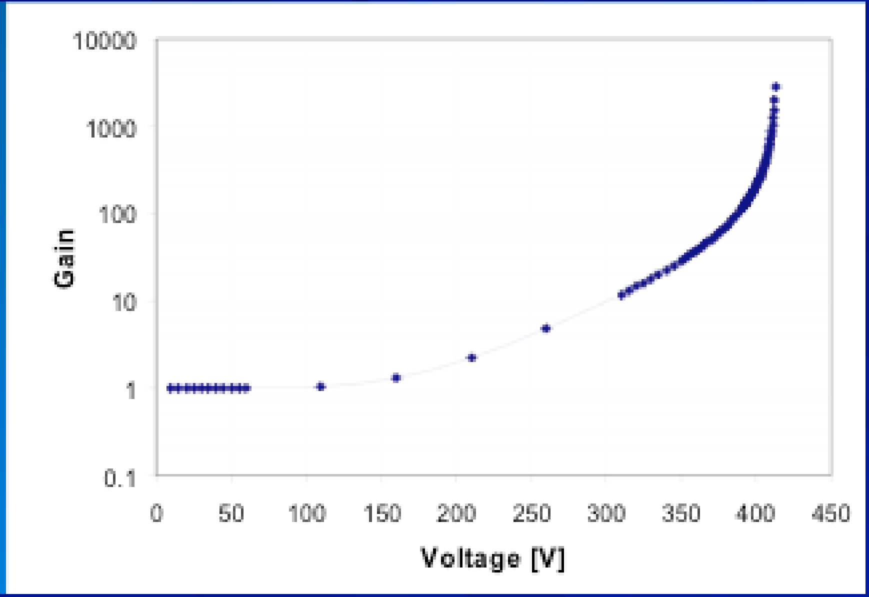
Relative temperature dependence of the gain plotted over the gain

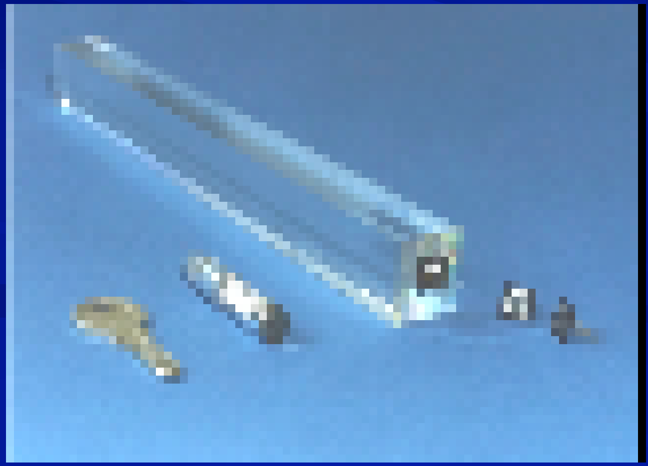


- The gain is an exponential function of the bias voltage. Therefore the relative change of the gain with voltage is a linear function of the gain (lower left plot).

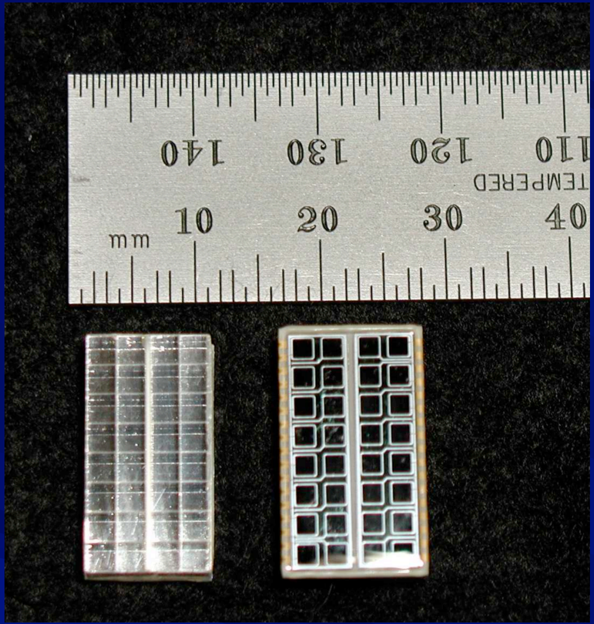
CMS EM calorimeter APD

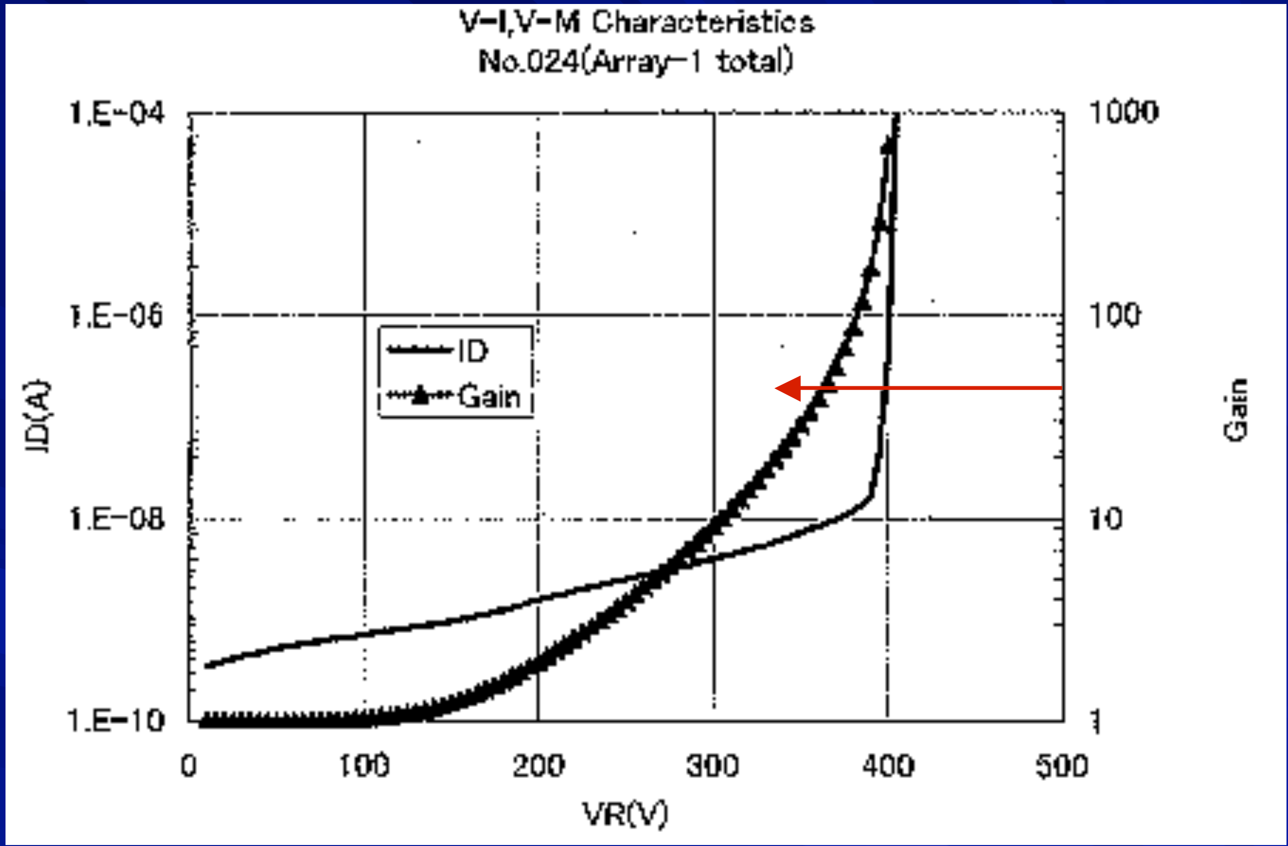






APD's Array





Hamamatsu S8550

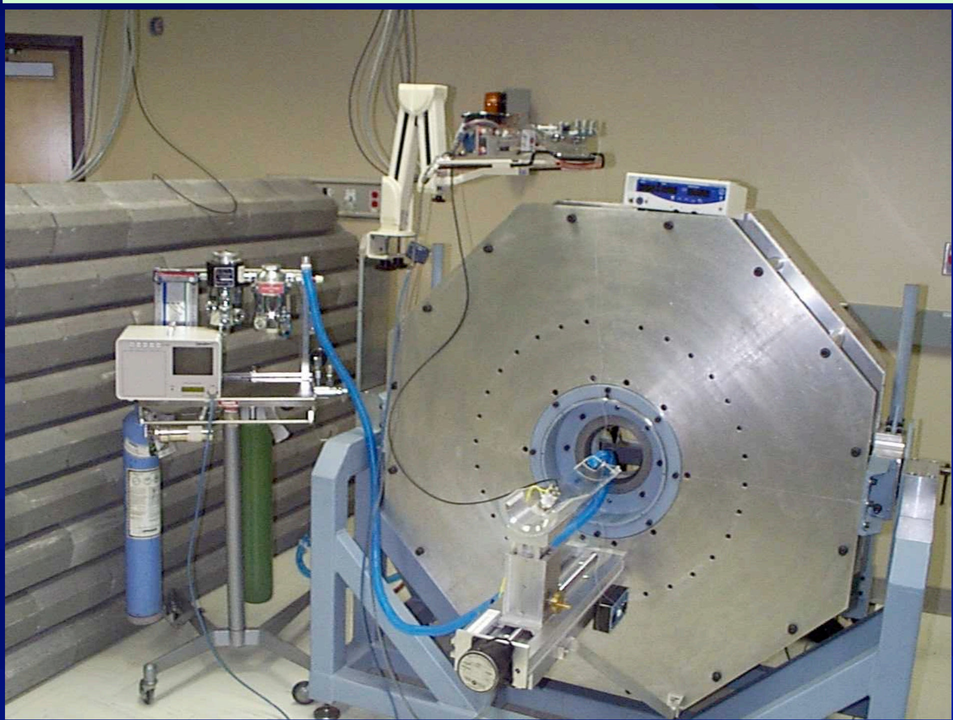
4x8 array
1.6 x 1.6 mm^2
active pixel area
C_T~ 10 pF

Typical G ~ 50
N_{pe} ~ 1200
~ 60K signal electrons

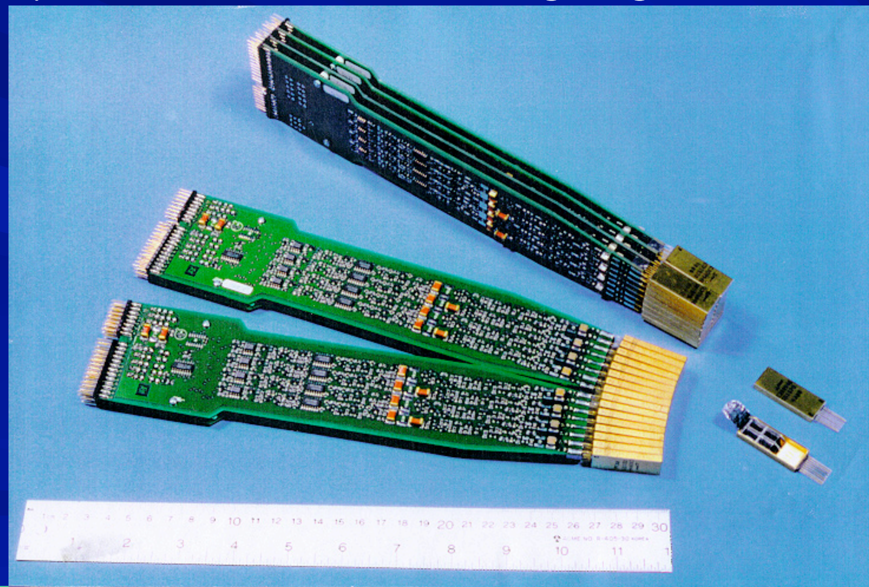
Expected noise in final ASIC ~ 500-600 e's

Sherbrooke Animal PET Scanner

Lecomte et al, *IEEE TNS* 43 (1996) 1952-7

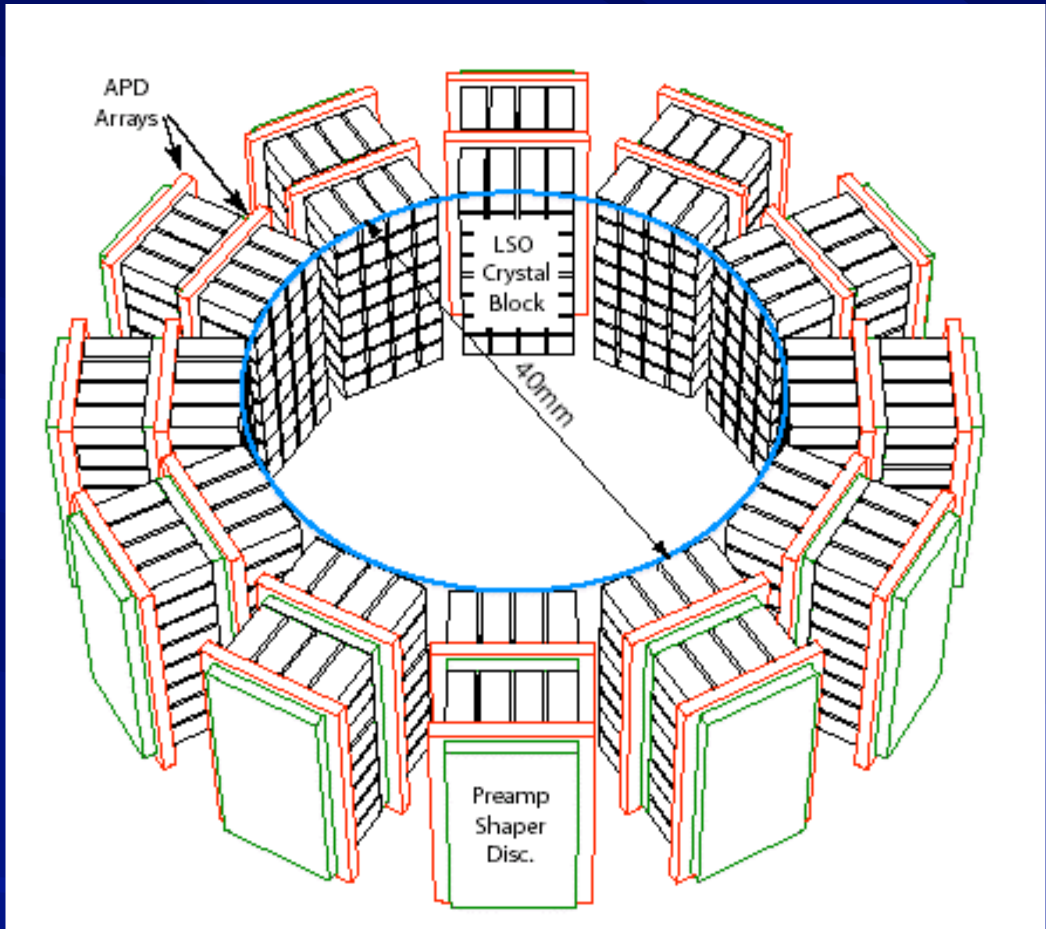


Scintillators	BGO
Photodetectors	Avalanche Photodiode
Crystal size	$3 \times 5 \times 20$ mm^3
Nb of detectors	512 / 32 cassettes (2×8 arrays)
Detector rings	2 (1 ring of modules)
Ring Diameter	310 mm
Animal Port	135 mm
Field-of-view	118 mm∅ × 10.5 mm
Nb of slices	3 (2 directs, 1 cross)
Coinc Time Window	20-40 ns (~25 ns)
Acquisition	List mode, gating



Resolution	$2.1 \times 2.1 \times 3.1$ mm^3 *or* 14 μl
Efficiency	200 cps/μCi (0.51%)
Sensitivity	2 kcps/μCi/ml/cm
Peak NEC	61 kcps (11 cm∅)

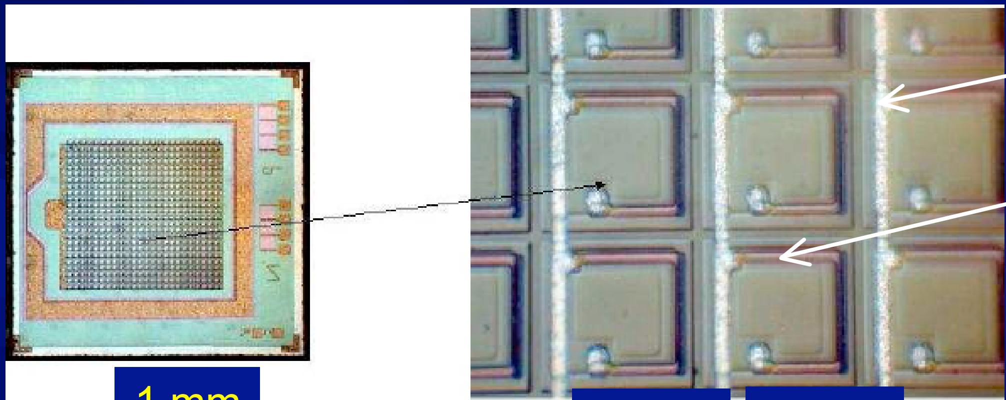
The Rat Conscious Animal PET scanner,
J.F. Pratte, et al., BNL

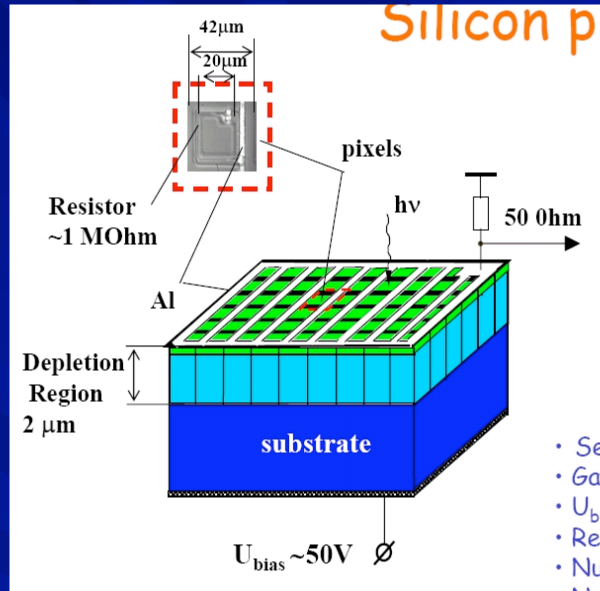


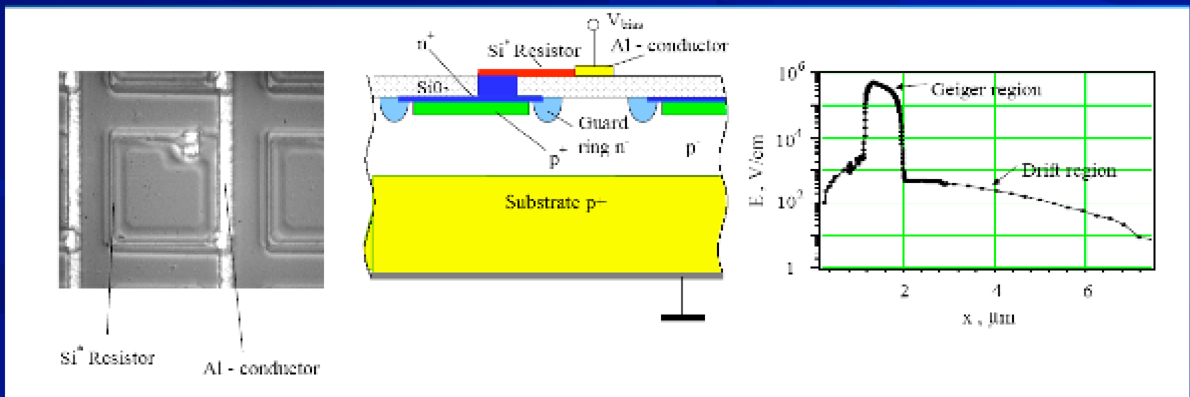
Ring containing 12 block detectors
Up to two layers of 2x2 x5 mm deep LSO crystals with APDs and integrated readout electronics

New photodetectors : Silicon Photo Multiplier

- Array of small APDs (20 X 20 μm^2) onto the same substrate
- Geiger discharge quenched by passive resistor (400kΩ) on each pixel
- Individual resistor with common read-out



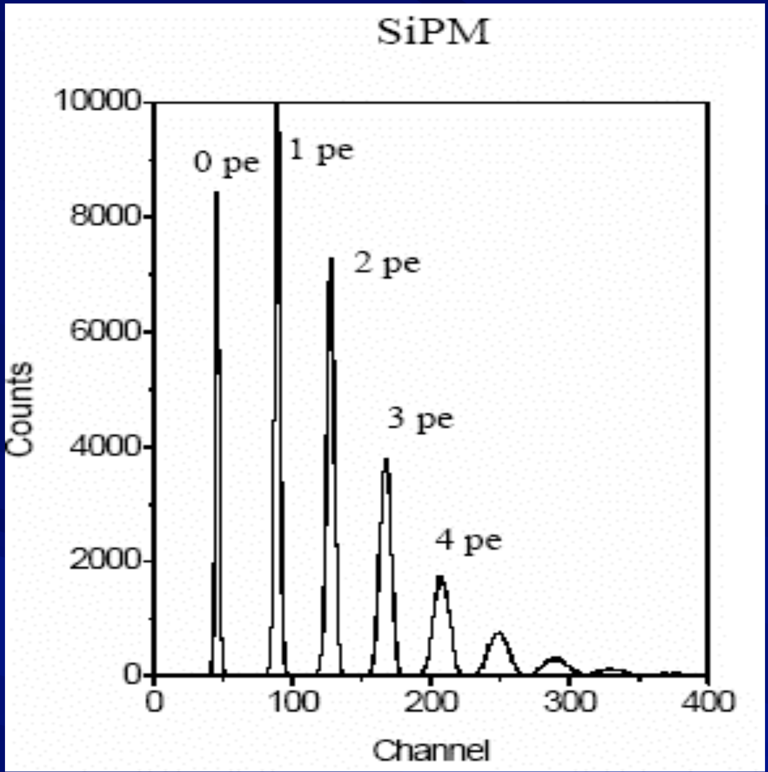


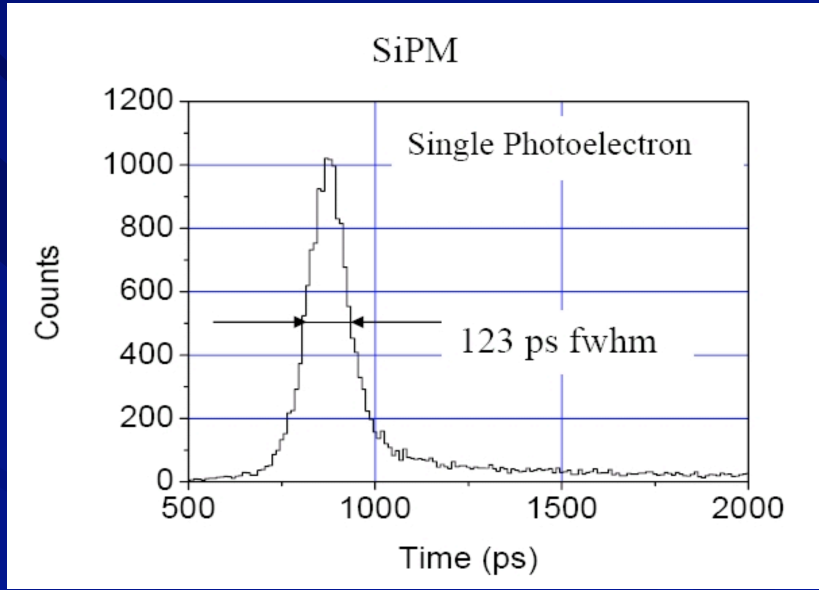


Small depleted layer (0.5 µm)
very highfield =>
Geiger avalanche

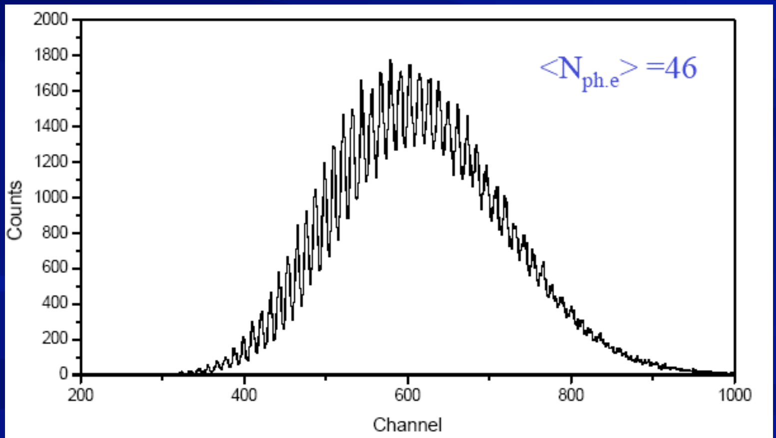
P. Buzhan, B. Dolgoshein et al ICFA 2001 MEPhI et PULSAR

SiPM





Contribution from the laser and the electronics is 40 ps each. time resolution 100 ps FWHM



Scintillator signal (MIP)

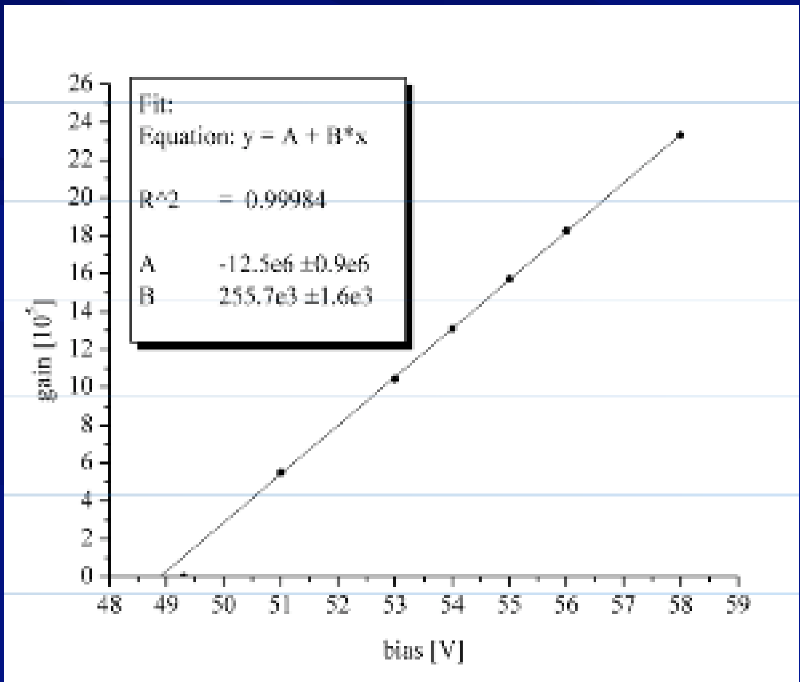
SiPM main features

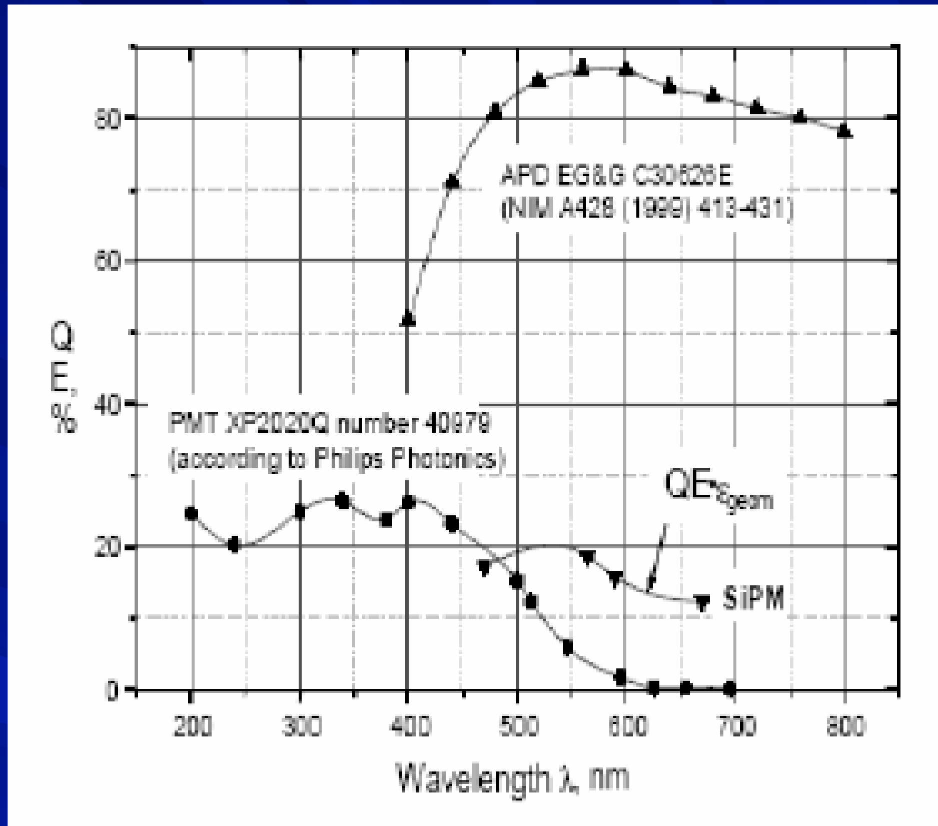
- Insensitive to magnetic field
- Sensitive size $1x1mm^2$
- Gain $\sim 2.10^6$ @ U_{bias} ~50V
- Recovery time ~ 100 ns/pixel
- Number of pixels: 1024 (Dynamic)
- QE ~20% @ 550nm (geometric)
- Dark noise Rate : ~1MHz/mm2 @ room temp
  ~1kHz/mm2 @ 100°K

taken from B. Dolgoshein's presentation in Beaune 2002 (NIM A 504 (2003) 48)

Solid State : SiPM (3)

- Some problems





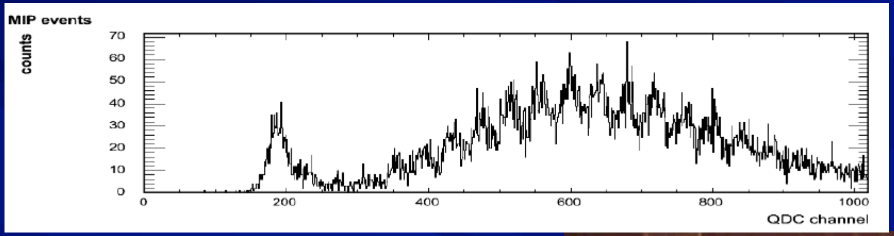
Dark noise vsbias voltage
Decrease to 10 kHz at -50₀C @ G= 106
layer

Quantum efficiency :
•Low for a Si device
•low fill factor
•thickness of front layer

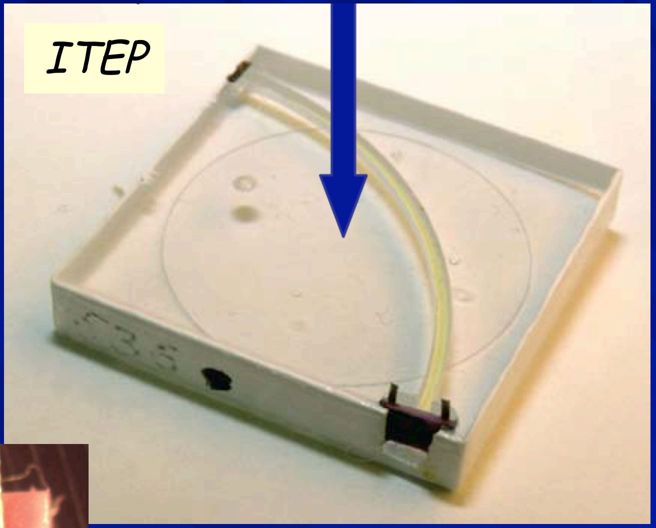
P. Buzhan et al. NIM A 504 (2003) 48-52

Si PM for ILC Hadron calorimetry

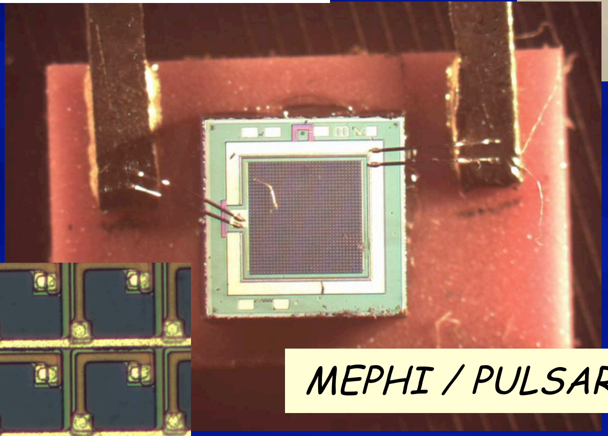
- Multipixel Geiger Mode APDs
  - Gain 10^6, bias ~ 50 V, size 1 mm^2
  - Insensitive to magnetic fields

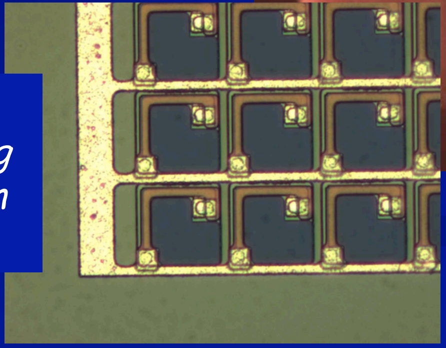


Auto-calibrating but non-linear



3x3 cm scintillator tile with WLS fibre





1156 pixels with individual quenching resistor on common substrate

New era for scintillator-based detectors:
High granularity** at relatively **low cost

(F.Sefkov)

SiPM development

- Very active field, driven by non-HEP applications
  - Medical imaging (PET), diagnostics, night vision, radiation monitoring
- More players entering:
  - MEPHI/PULSAR, CPTA, JINR, MPI-Munich, Hamamatsu, SensL,...
- Directions: higher signal – lower noise -cost
  - Lower noise and / or inter-pixel Xtalk → lower thresholds
  - Better spectral sensitivity – to blue scintillation light
  - Larger area and / or better geometrical packing factor
- Will allow to
  - Significantly simplify the coupling between SiPM and scintillator
    - Eliminate fibre, ease precision requirements
  - Or: Use thinner scintillator